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RESULTS OF TESTING THE AEDC 5-MW SEGMENTED ARC HEATER AT PRESSURES UP TO 171 ATM

PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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Prepared for

DIRECTORATE OF TECHNOLOGY (DY)
ARNOLD ENGINEERING DEVELOPMENT CENTER
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NOTICES

APPROVAL STATEMENT

This technical report has been reviewed and is approved for publication.

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The results of testing a nominal 5-MW segmented (constrictor-channel type) arc heater are presented. The heater was operated at chamber pressures up to 171 atm and power inputs to nearly 4 MW using air as the test gas. Bulk enthalpies ranged from about 5,700 Btu/lb at 60 atm to 3,500 Btu/lb at 153 atm. The nozzle exit flow was surveyed with a null-point calorimeter, pressure, and enthalpy probes. Performance comparisons are made between the

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20. ABSTRACT (Continued)

segmented and other types of arc heaters and with an analytical correlation program. Detailed test and data summaries are presented.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results presented in this report were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was done under ARO Project No. P32S-21A. The authors of this report were Dennis D. Horn and Richard T. Smith, ARO, Inc. The manuscript (ARO Control No. ARO-PWT-TR-75-85) was submitted for publication on June 20, 1975.

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

In 1967, the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), contracted with Electro-Optical Systems, Inc. (EOS) to study and develop an untrahigh-pressure arc heater (Refs. 1 and 2). This effort resulted in the delivery of a constricted-channel, segmented arc heater to AEDC in 1969. The specific goal for this d-c arc heater was to heat air to 3,830 Btu/lb bulk enthalpy at 200 atm chamber pressure with a power input of 5 MW. The results of operating this heater through June 1970 at AEDC are presented in Ref. 3. Various hardware problems prevented stable operation above 25 atm.

This heater was extensively modified and experimental efforts were resumed during Fiscal Year 1972 (FY72). Thereafter, this modified heater was referred as the 5-MW Segmented Arc Heater. The specific objectives were to operate the heater on air at chamber pressures of 25, 50, 80, and 100 atm, and obtain steady-state bulk enthalpies at arc current levels of 400, 500, and 600 amp. The results of operating the heater during FY72, 73, and 74 are presented in detail in Ref. 4. The highest pressure at which the heater was tested during that test series was 104 atm.

The results of testing the 5-MW segmented arc heater during FY75 are reported herein. The specific objectives of this effort were to obtain performance data at chamber pressures up to 150 atm, to make an endurance run up to 1 min long at a pressure level of at least 100 atm, and to provide hardware design criteria for a large-scale segmented arc heater. The long-range objectives of the 5-MW segmented arc research effort were to provide performance and design data in support of the large-scale segmented heater and to upgrade and make available an operational version of the 5-MW segmented arc heater for user ablation testing and in-house research.

2.0 TEST FACILITY AND PROCEDURE

The tests were conducted in the 5-MW Research Arc Heater Unit of the Propulsion Wind Tunnel Facility (PWT), AEDC.

2.1 ELECTRIC POWER AND OTHER UTILITIES

Electric power was supplied to the arc heater through a series of transformers and an ignition rectifier. The characteristics of this d-c supply are shown in Fig. 1. Ballast resistance up to 9.3 ohms was added as necessary to provide current control and improve arc stability. High-pressure air (up to 4,000 psia) was supplied by the AEDC von Kármán Gas Dynamics Facility (VKF) either from a storage bottle or directly from compressors, through a pressure control and metering station. Demineralized cooling water was supplied to the arc heater by two centrifugal pumps, each rated at 120 gpm at 1,200 psig. Raw water for nozzle cooling was supplied by a centrifugal pump rated at 200 gpm at 1,200 psig.

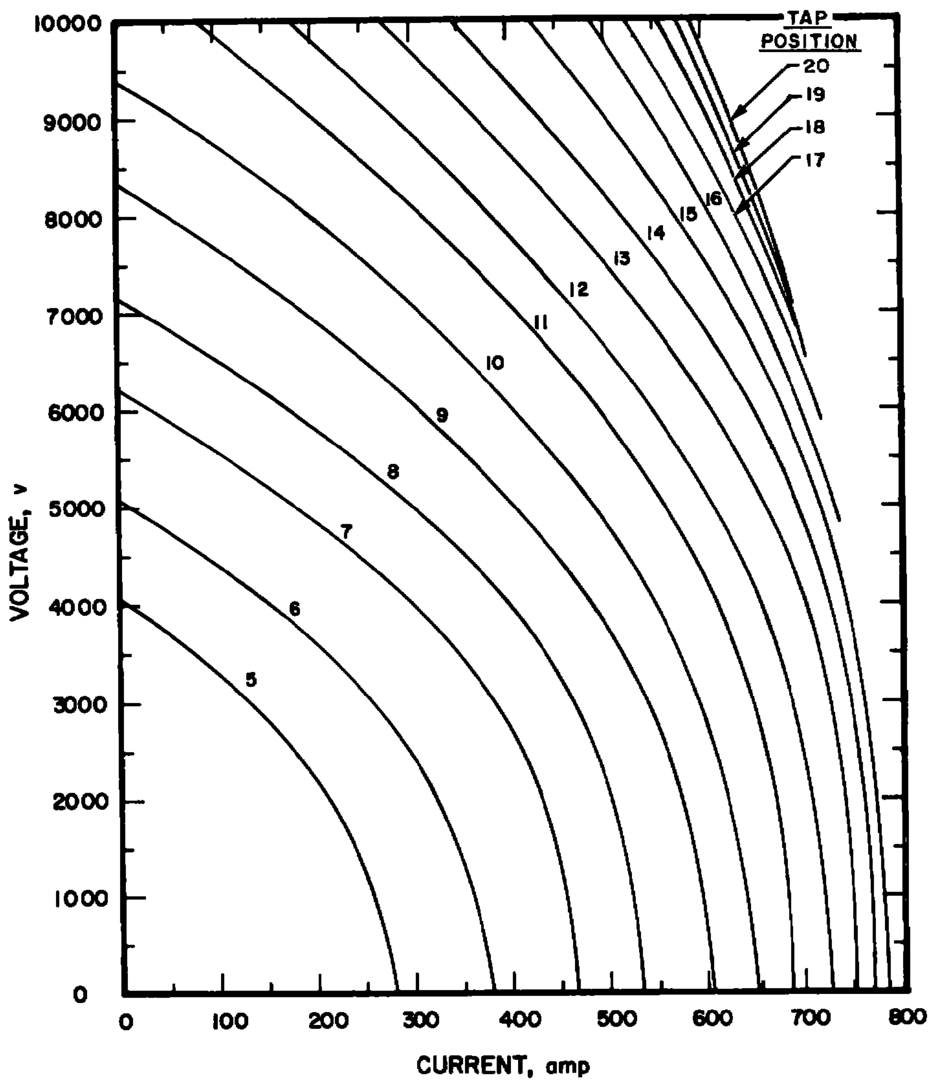


Figure 1. Characteristics of the AEDC nominal 5-MW power supply.

2.2 INSTRUMENTATION

Strain-gage transducers, thermocouples, voltage dividers, current transducers, and turbine-type flowmeters were sensors for the pressures, temperatures, arc voltage and current, and cooling-water flows. These parameters were recorded on strip chart recorders for steady-state values; transient and redundant parameters were recorded on oscillographs. Air mass flow rate was measured using a choked venturi which was calibrated by flowing air into a tank and weighing on precision scales. Control room data were obtained from panel meters and strip chart recorders. Closed-circuit television was used to monitor the arc heater and models during operation.

Model instrumentation included a 0.25-in. nose radius null-point calorimeter, an impact pressure probe, and a total enthalpy probe (Ref. 5). These probes were swept through the heater effluent consecutively, using a five-position linear model injection system (Ref. 6). Model tips were positioned 0.1 in. downstream of the nozzle exit, and the sweep rate was approximately 32 in./sec. Surveillance of the heater, models, and effluent was done by the use of high-speed motion pictures.

2.3 ARC HEATER

The initial arc heater configuration used for this test series is shown in the photograph in Fig. 2 and the schematic in Fig. 3. Operating configurations prior to FY75 are

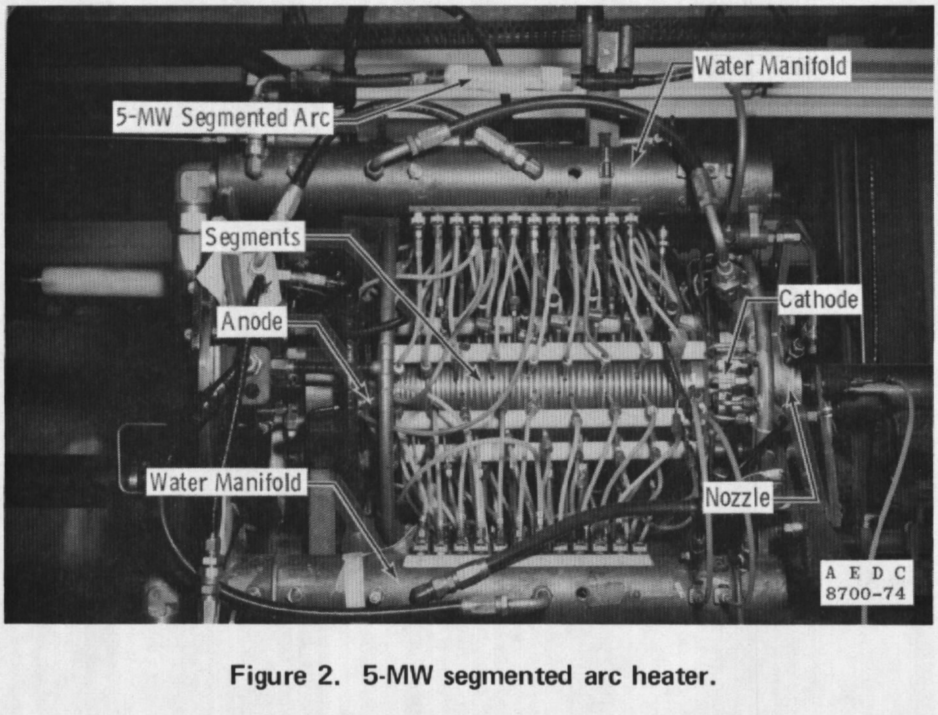


Figure 2. 5-MW segmented arc heater.

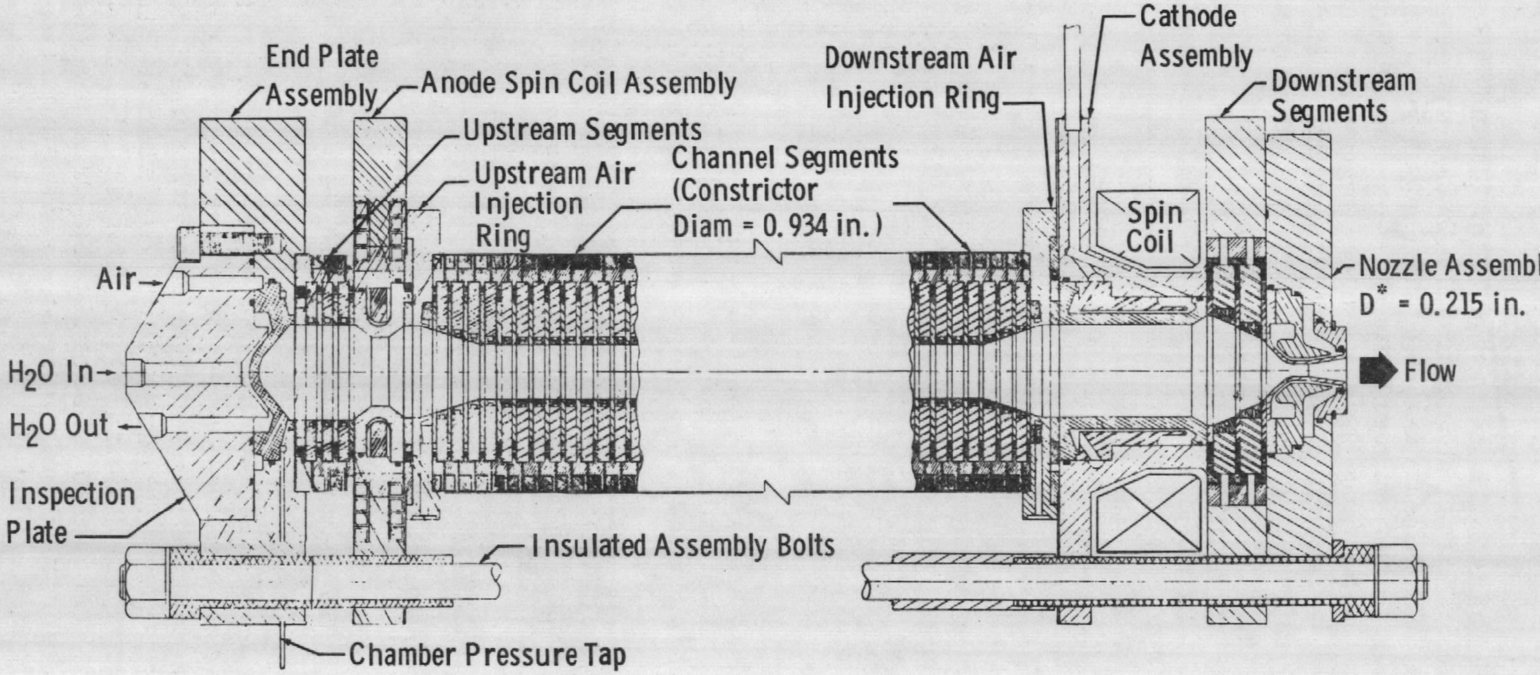


Figure 3. Initial 5-MW segmented arc heater configuration.

described in detail in Ref. 4. The heater consisted of a constrictor channel made up of water-cooled copper segments separated by 0.081-in.-thick boron nitride insulators. The channel had an internal diameter of 0.934 in. and consisted of 55 segments, including three tapered segments and an air injection ring at each end. The straight portion of the channel contained ten AEDC-welded segments 0.187 in. wide and 37 AEDC-silver-soldered segments 0.250 in. wide (see Fig. 4).

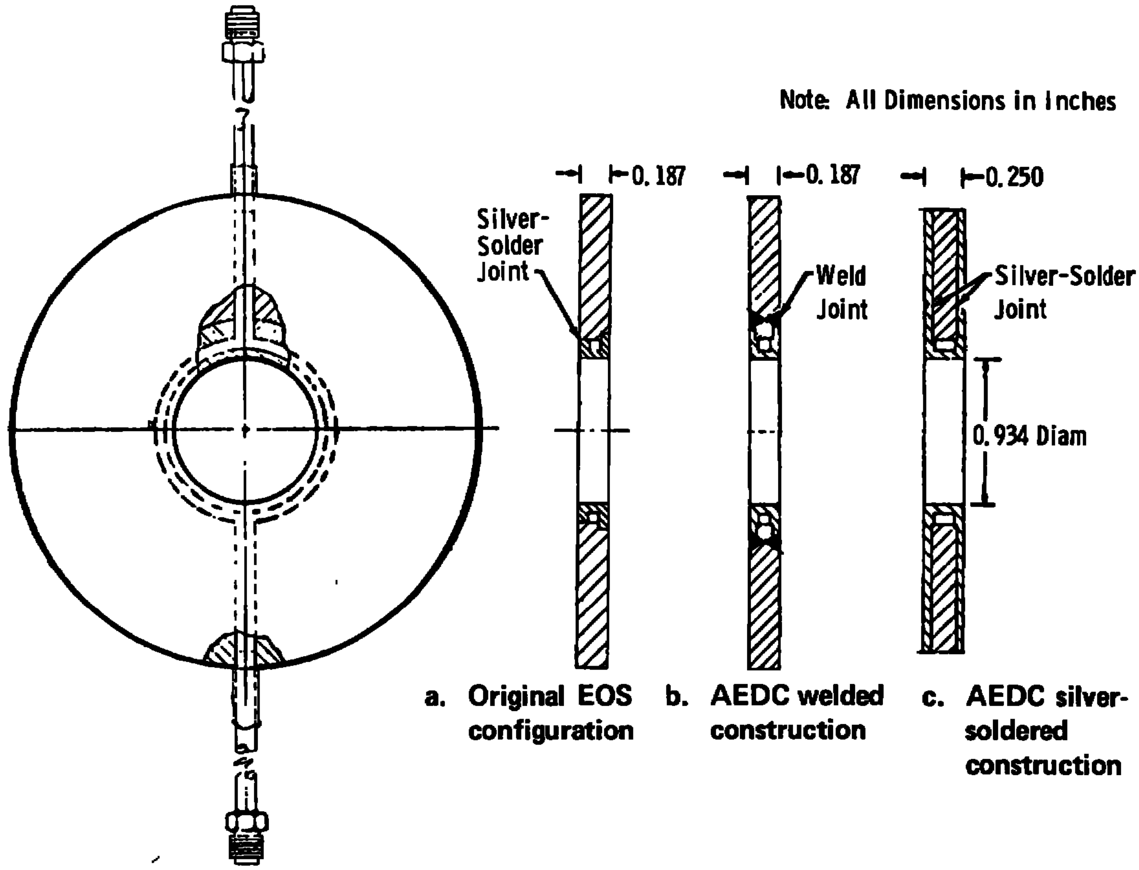


Figure 4. Various segment designs used on the 5-MW segmented arc heater.

A ring electrode located at the upstream end of the channel served as the anode. A magnetic coil, encapsulated in plastic and consisting of eight turns of square copper tubing, formed the external part of the electrode ring assembly. A new cathode assembly located at the downstream end of the channel contained a short tubular electrode surrounded by a hand-wound magnetic coil of approximately 15 turns of insulated, water-cooled copper tubing.

The coils were electrically connected in series with the arc column; the polarity was selected to augment the air swirl and stimulate rotation of the arc termination on the electrodes. The heater was operated with reversed polarity throughout the test series, i.e., the anode was the upstream electrode. The axial distance between electrodes was approximately 18 in.

Four upstream segments were positioned between the anode and end plate assembly, each electrically insulated with boron nitride spacers. These segments, coupled with tangential air injection at the end plate liner, prevented arc attachment on the end plate. Two downstream segments provided a transition section for the flow entering the nozzle throat. The conical nozzle had a 0.215-in. throat diameter and a 0.400-in. exit diameter. Air was introduced at the upstream and downstream air injection rings and at the end plate liner in various ratios controlled by orifices in the supply lines as indicated in Table 2. Swirl direction for all air stations was clockwise looking downstream.

The configuration changes made to the heater at the beginning of this test series were as follows:

1. The end plate assembly was modified to include an inspection plate. This allowed the inner liner to be removed for in-place inspection of the upstream portion of the arc heater.
2. A new cathode assembly (described above) was installed to provide a more durable electrode surface, to lower erosion rates, and to allow in-place inspection of the downstream end of the heater. The flange on the upstream end of the cathode assembly were used to hold the heater together while the nozzle and downstream segments were removed for inspection.

Subsequent modifications and configuration changes are covered in Section 3.0.

2.4 PROCEDURE

2.4.1 Pretest Procedure

The arc heater was installed on the test stand; all air, water, and instrumentation connnections were completed; and the instrumented probes were aligned to the nozzle exit.

Test voltage was then applied to ensure that external insulation was adequate up to 12.5 kv. The heater chamber was connected to a vacuum system by a breakaway seal at the nozzle exit. The heater was checked for gas leaks with the pressure maintained at a level near 1 mm Hg. Test voltage was again applied to ensure that starting breakdown voltage within the heater was below 8 kv. Cooling water was supplied to the heater at the scheduled operating pressure and flow rate, and a leak check of all cooling components was performed. The water system was then secured, and routine instrumentation and auxiliary system preoperational procedures were completed. The vacuum was maintained throughout the pretest procedures. The regulated air supply was preset for the pressure required for the run, and the electrical leads were attached to the heater. The heater was then ready for operation.

2.4.2 Starting and Operating Procedure

The transformer tap position was set for the scheduled power level. The cooling-water systems were energized manually, proper flow rates established, and interlocks set. After checking the regulated air pressure and heater vacuum, the instrument recording systems were started. Electrical power to the heater was energized. When breakdown occurred and current was established, the air valve was opened automatically using the signal from a current-sensing device. Time required from arc initiation to full pressurization was about 1.5 sec. Nearly 8 to 10 sec were required for cooling water temperatures to stabilize for an energy balance. Models were injected as required during heater operation. For a normal shutdown, power termination automatically closed the air valve; then, cooling water and other support systems were manually secured. The heater conditions were preset for all runs and were not adjusted during any given run.

3.0 TEST DESCRIPTION AND RESULTS

3.1 RUN SUMMARY

Test summaries for the experimental effort are shown in Tables 1 and 2. Table 1 provides a summary of the test conditions and resulting heater performance and model data. Table 2 is a summary of test objectives, hardware configurations, and general remarks.

The heater was initially operated on October 10, 1974. The hardware configuration was described in Section 2.3 and is shown in Fig. 3. A shakedown run (Run 1) was made at 50.5 atm chamber pressure, and energy balance runs (Runs 2 and 3) were made at 58.5 and 107 atm, respectively, to verify proper operation of the arc heater and to check the instrumentation by comparing the data with previous runs reported in Ref. 4.

Runs 4, 5, 6, and 7 were made at chamber pressures of 124, 130, 153, and 171 atm, respectively, in an effort to extend the operating pressure range of the segmented arc heater. Run 4 was a checkout run of 5.2 sec. Runs 5 and 6 were energy balance runs of 12 sec each and were so successful that disassembly of the heater was not required after either run. On Run 7 a channel segment failed at 2.8 sec, and the run was terminated at 3.1 sec. The chamber was fully pressurized after 1.7 sec, and at 2.0 sec a pressure pulse (lasting 0.05 sec) resulted in a momentary peak pressure of 186 atm in the heater. The inside walls of six channel segments partially collapsed from the pressure load. These segments were designed for a maximum gas pressure of 125 atm.

Runs 8 through 11 were made with a standard tubular Linde-type anode assembly adapted to the segmented arc heater (see Fig. 5). The purpose of this modification was to determine operational feasibility of a proven anode configuration and to evaluate heater performance. The effective arc length of the heater with this anode was about 24 in. This was accomplished by replacing all hardware upstream of the straight channel with the new anode assembly, body shell, air injector ring, and a body-to-segment transition piece. Runs 8 and 9 were shakedown runs with the new configuration. Run 8 resulted in an external insulation breakdown. Run 9 was a successful 5-sec run at 55 atm. An energy balance run (Run 10) was then made at 60 atm. The heater operation was normal for 6.6 sec, then the arc length shortened and the anode attachment relocated at the downstream end of the tube. Stable energy balance data points were recorded for both modes of operation and are presented in Table 1, Runs 10-1 and 10-2. No damage resulted from either mode of operation. Run 11 was an energy balance attempt at 102 atm; however, at 4.3 sec, three channel segments failed. No other damage occurred, and heater operation appeared normal prior to the segment failure.

At this point, the Linde-type anode configuration was replaced with the original ring anode (Fig. 3) in preparation for the evaluation of a new prototype segment design planned for the large segmented arc heater currently under design at AEDC. Runs 12 and 13 were check runs to ensure the heater was operating properly before the prototype segments were installed. Run 12 was inadvertently terminated at 1.1 sec. On Run 13, an energy balance was obtained at 107-atm chamber pressure with

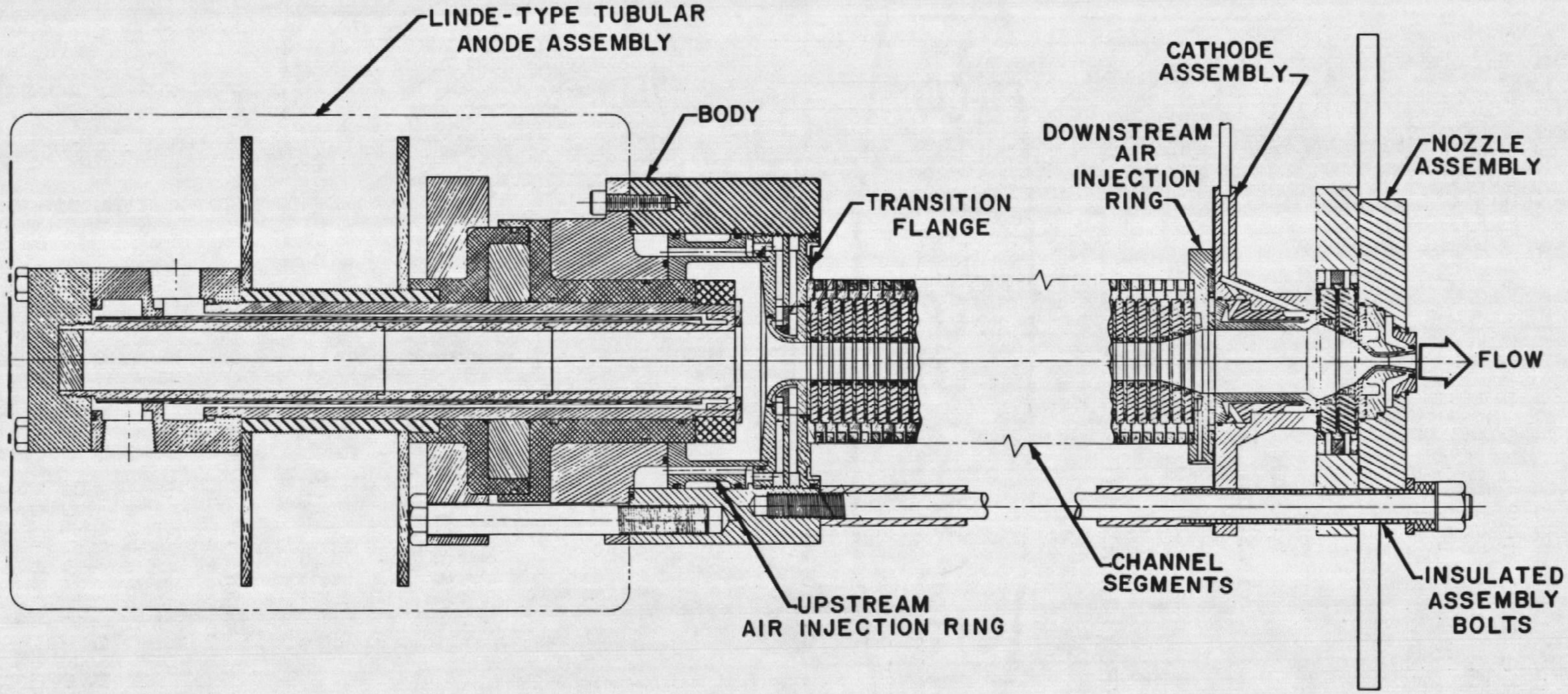


Figure 5. 5-MW segmented arc heater with Linde-type tubular anode assembly.

no problems encountered. The purpose of Runs 14, 15, and 16 was to evaluate the new prototype segment design (see Fig. 6). The major improvements in the prototype segments included (1) radiation shielding of the insulators between segments, (2) thicker segment walls to withstand higher gas pressure, and (3) provision for air injection between segments. Three

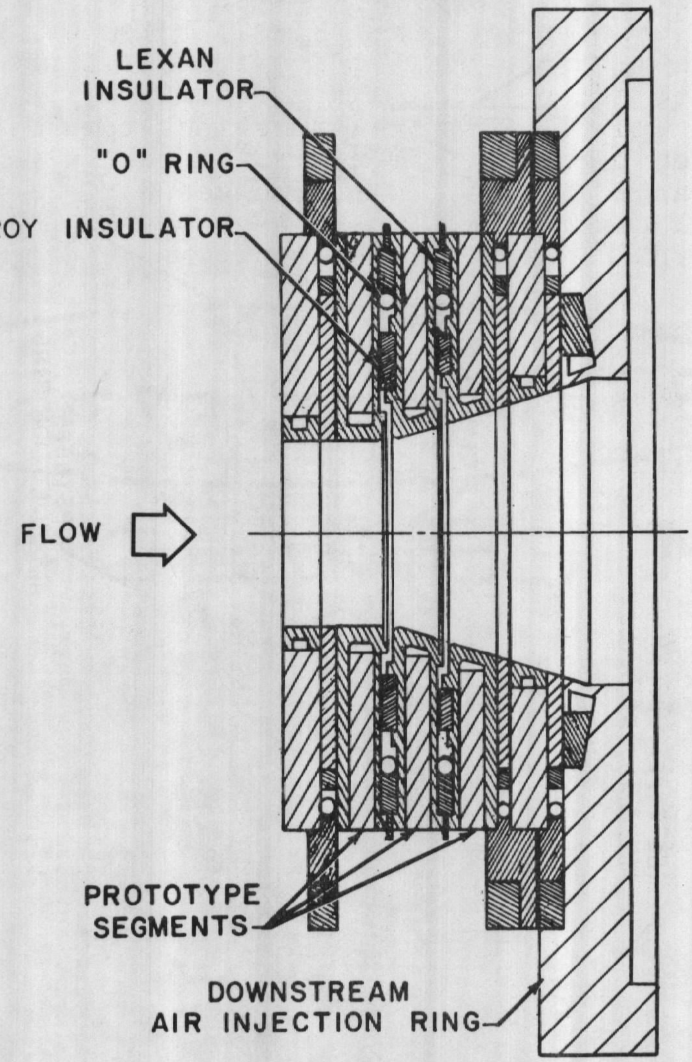


Figure 6. Prototype segment configuration.

new prototype segments were installed (Fig. 6) on Run 14. The heater was operated for 8 sec at 104-atm pressure. In general, the prototype segments were undamaged except for some minor erosion which occurred on one prototype segment, indicating some local arcing at the wall. An energy balance attempt on Run 15 resulted in a channel segment failure at 130 atm after 2.4 sec. Also, the wall of two of the prototype segments partially collapsed. Since defects had occurred during fabrication, the three prototype segments were replaced with two new prototype segments and a standard channel segment. A successful energy balance was made (Run 16) for 10 sec at 132 atm. The prototype segments were undamaged, and the general condition of the heater after the run was good.

The final run of this test series was an endurance run at 105-atm chamber pressure. The purpose was to verify that longer runs with the segmented arc at high pressures are feasible, to determine if a degradation of performance occurred with time, and to verify that previous runs of 8 to 12 sec were of sufficient length to obtain valid energy balances for the segmented arc. The heater ran successfully for 60 sec, and the general condition of the heater was excellent after the run. Moderate erosion of the anode ring was evident after the run.

3.2 ARC HEATER DATA

3.2.1 Heater Performance and Data Correlation Program

Measured bulk enthalpies for the 5-MW segmented arc heater are shown in Fig. 7 for various chamber pressures and electrical currents. Data from FY72, 73, and 74 are included

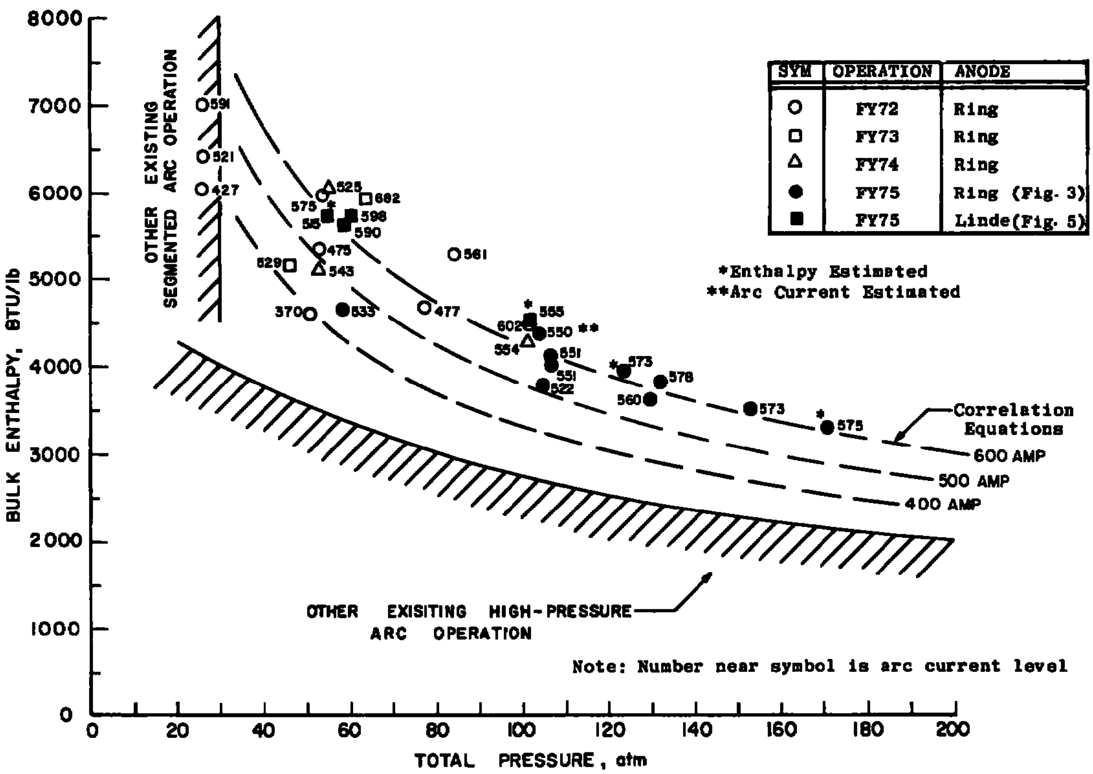


Figure 7. 5-MW segmented arc heater performance data.

to provide a more complete data history of the heater. Also, since the heater was operated in a new test location with different instrumentation during FY75, it was desirable to verify that the performance data would repeat. Several FY75 data points near 60 atm and 105 atm show excellent repeatability with previous data. Measured performance ranged from about 5,700 Btu/lb at 60 atm to 3,500 Btu/lb at 153 atm. The Linde-type anode configuration did not show a significant improvement in enthalpy for the few runs attempted.

A data correlation program was formulated by Aerotherm Division, Acurex Corporation, under AF Contract F40600-74-C-0015 (Ref. 7), based on previous energy balance data from the AEDC 5-MW segmented arc heater. This correlation was modified at AEDC to provide better agreement with the data and the following relationships were obtained:

$$V_{corr} = 430\left(\frac{L}{D}\right)^{0.75} \dot{m}^{0.4}\, p_o^{0.165}, \text{ volts} \tag{1}$$

$$H_{corr} = 4.818\left(\frac{I}{\dot{m}}\right)^{0.5}\left(\frac{L}{D}\right)^{0.825} p_o^{0.1}, \text{ Btu/lb} \tag{2}$$

The sonic flow enthalpy equation (Winovich, Ref. 8) was used in conjunction with Eqs. (1) and (2):

$$\frac{\dot{m}}{A^* p_o} = 280\, H_s^{-0.397} \tag{3}$$

where

L = arc channel length, in.

D = channel bore diam, in.

$\dot{m}$ = air mass flow rate, lb/sec

p_o = total pressure, atm

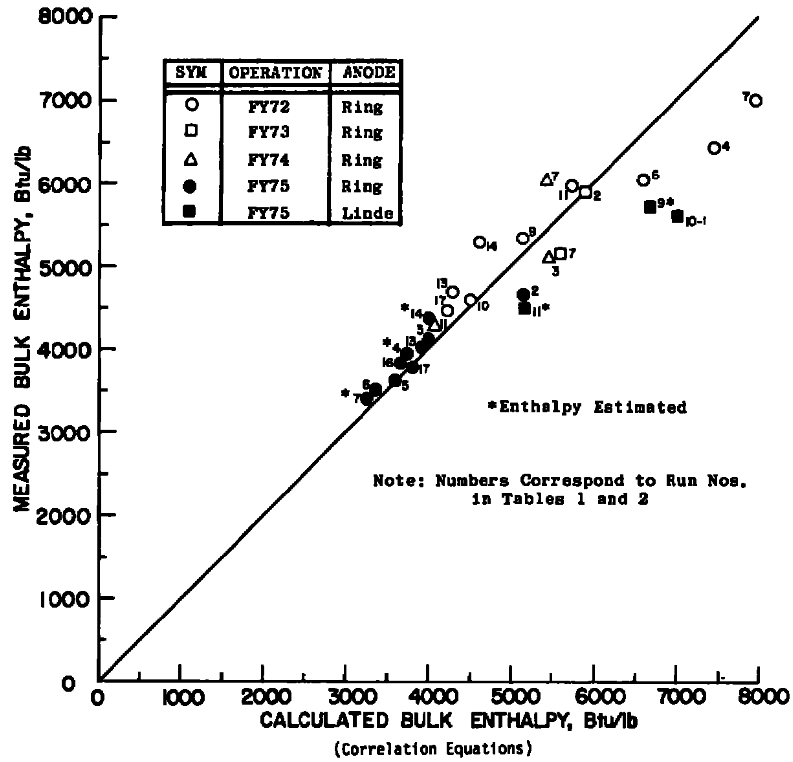
I = arc current, amp

A^* = sonic throat area, ft^2

H_s = enthalpy based on sonic flow equation, Btu/lb

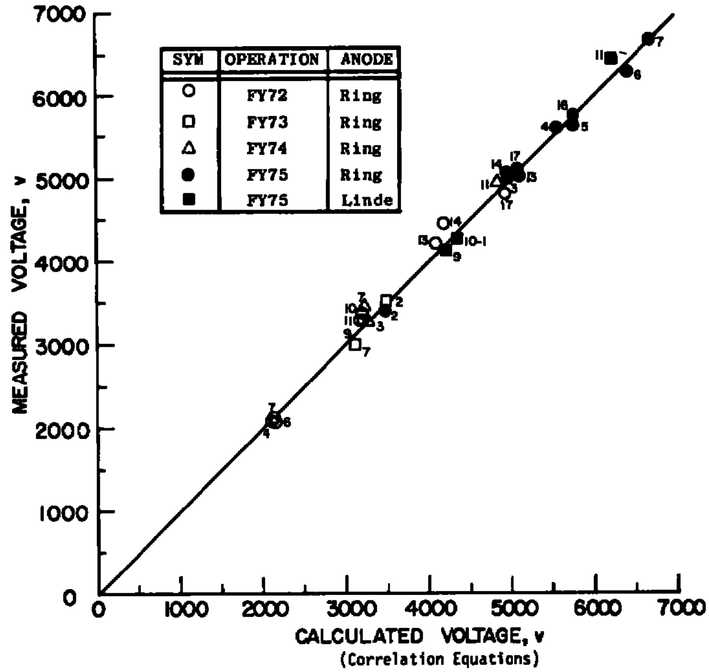
With the correlation equations, enthalpy values were calculated for currents of 400, 500, and 600 amp using the geometry of the 5-MW segmented arc heater. These values are superimposed on the data in Fig. 7. In general, the agreement is good between the measured and calculated enthalpies. Further comparisons of enthalpy, arc voltage, and chamber pressure are presented in Figs. 8a, b, and c, respectively.

Agreement is excellent between measured and calculated values of voltage and pressure and generally good for enthalpy. More data scatter was expected in enthalpy because a minimum of 5 input parameters is required to perform an energy balance. Calculated enthalpies were consistently higher than measured values for the 26 atm pressure runs (FY72 Runs 4, 6, and 7) and for the Linde-type anode runs. This leads to the conclusion that efficiencies for these runs were lower than predicted, since the voltage levels were as predicted.

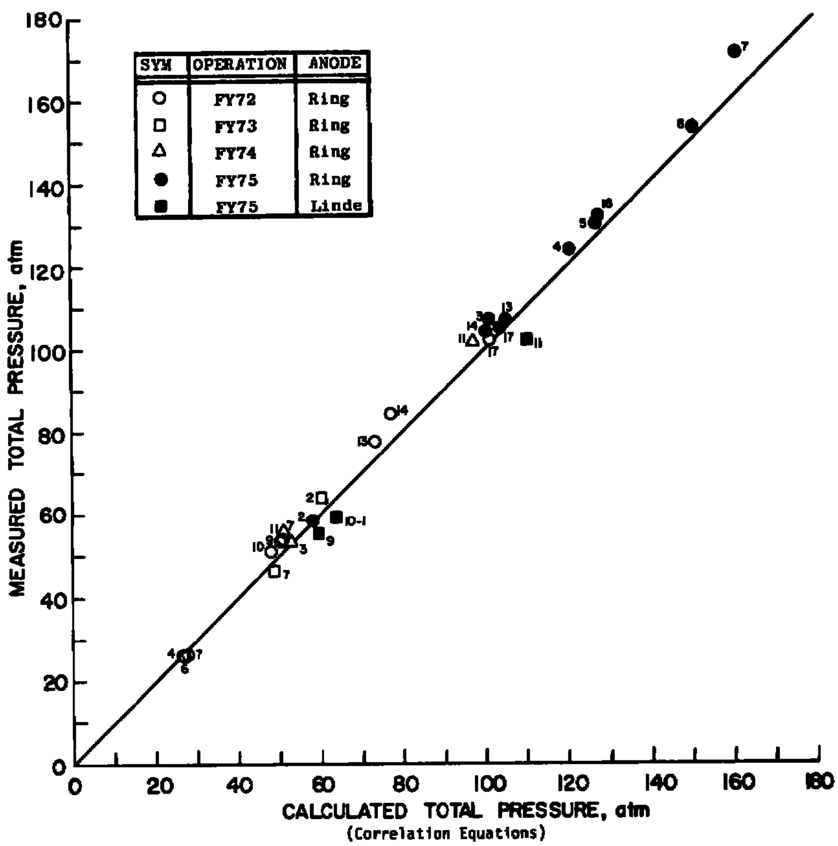


a. Bulk enthalpy

Figure 8. Comparison of measured and calculated values of arc heater parameters.



b. Arc voltage



c. Total pressure

Figure 8. Concluded.

In order to determine if the Winovich sonic flow equation (Ref. 8) were valid for this heater, a logarithmic plot of measured values of $\dot{m}/A^*p_o$ versus H_o was made (see Fig. 9). The data scatter was relatively small and a linear relationship evident. The expression resulting from a least squares linear curve fit of the data was

$$\frac{\dot{m}}{A^* p_o} = 316\ H_o^{-0.414} \tag{4}$$

This equation and the Winovich equation are superimposed on the data in Fig. 9. Either Eq. (3) or (4) can be used to calculate a reasonably accurate bulk enthalpy for this heater.

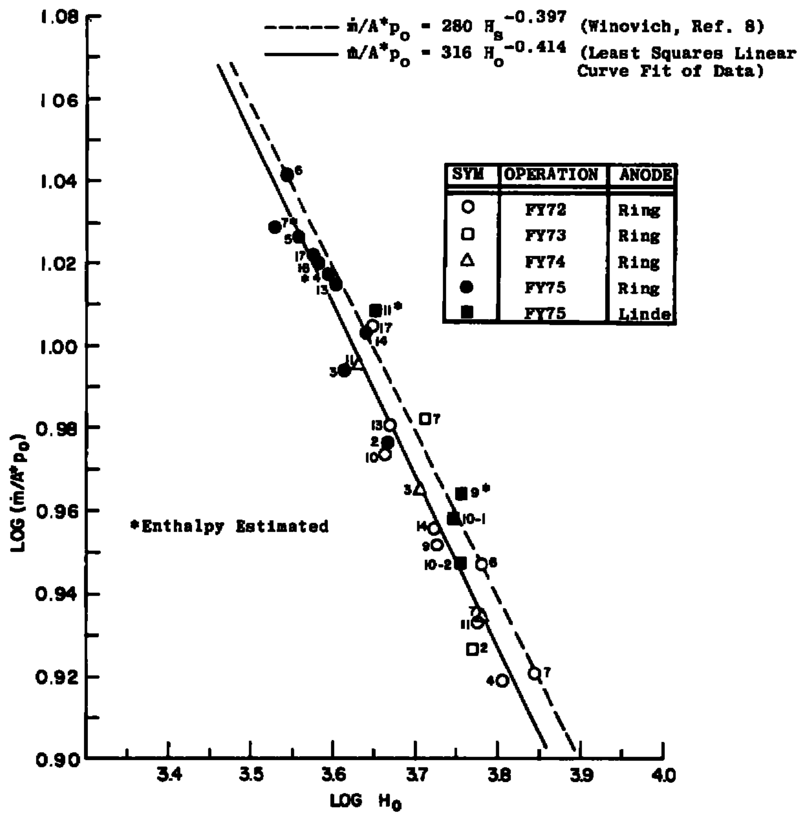


Figure 9. Comparison of arc heater data with sonic flow equation.

3.2.2 Channel Segments

The channel segment designs used in FY75 are shown in Fig. 4. The segment with the silver-solder construction (Fig. 4c) was considered superior because the wall exposed to gas pressure (extending past the gas seal) was continuous and any water leaks which did occur were external to the arc heater. However, the additional width of unsupported inner wall made these segments more susceptible to wall deformation at pressures greater than 100 atm. A photograph of a normal and a partially collapsed wall is shown in Fig. 10. No segment problems were encountered until the 171-atm run (Run 7),

CONFIGURATION: Silver-Soldered (Fig. 4c)

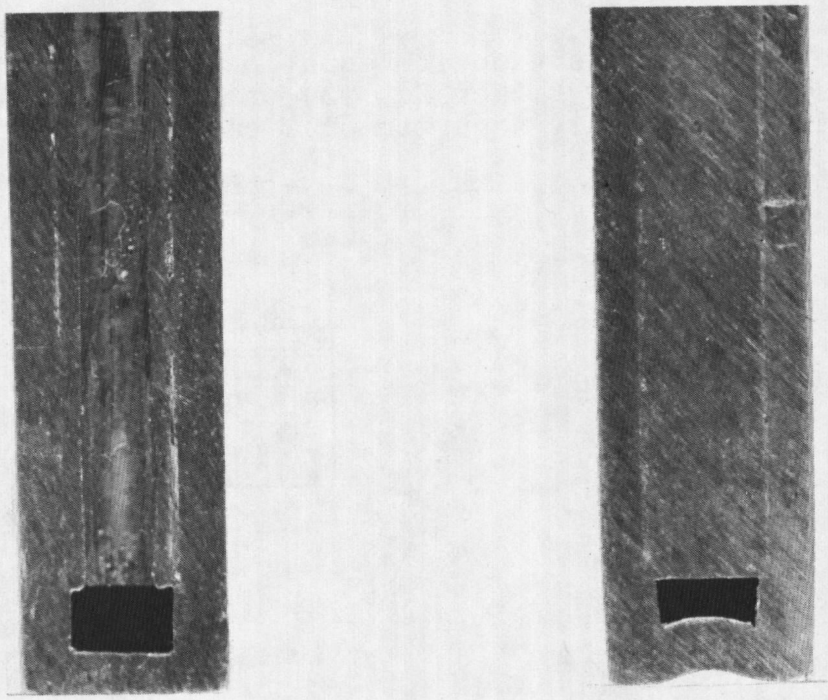


Figure 10. Channel segment wall cross section.

during which several silver-soldered segments developed partially collapsed walls. Most of the segment failures which occurred on later runs were attributed to the partial segment damage which occurred on Run 7. The welded segments Fig. 4b) were not deformed by the high-pressure gas, but water leaks which developed at the weld joint were internal to the heater. In general, these segments would not withstand the high heating rates required, and therefore, were located near the upstream end of the channel. The original EOS segments (Fig. 4a) were used only as spares or replacements for failed or damaged segments which occurred during testing. These segments were very susceptible to water leakage at the silver-solder joint.

Average measured wall heat flux of the channel segments is shown in Fig. 11 for all runs where data were available.

Measurements of rise in water temperature at eight segment locations along the channel were used to determine average fluxes. Heat fluxes ranged from below 3,000 Btu/ft^2-sec at 50 atm to nearly 6,500 Btu/ft^2-sec at 153 atm. Calculated heat fluxes based on the correlation program (Eqs. (1) and (2)) for arc currents of 400, 500, and 600 amp are also shown in Fig. 11. The agreement between calculated and measured heat fluxes was generally good.

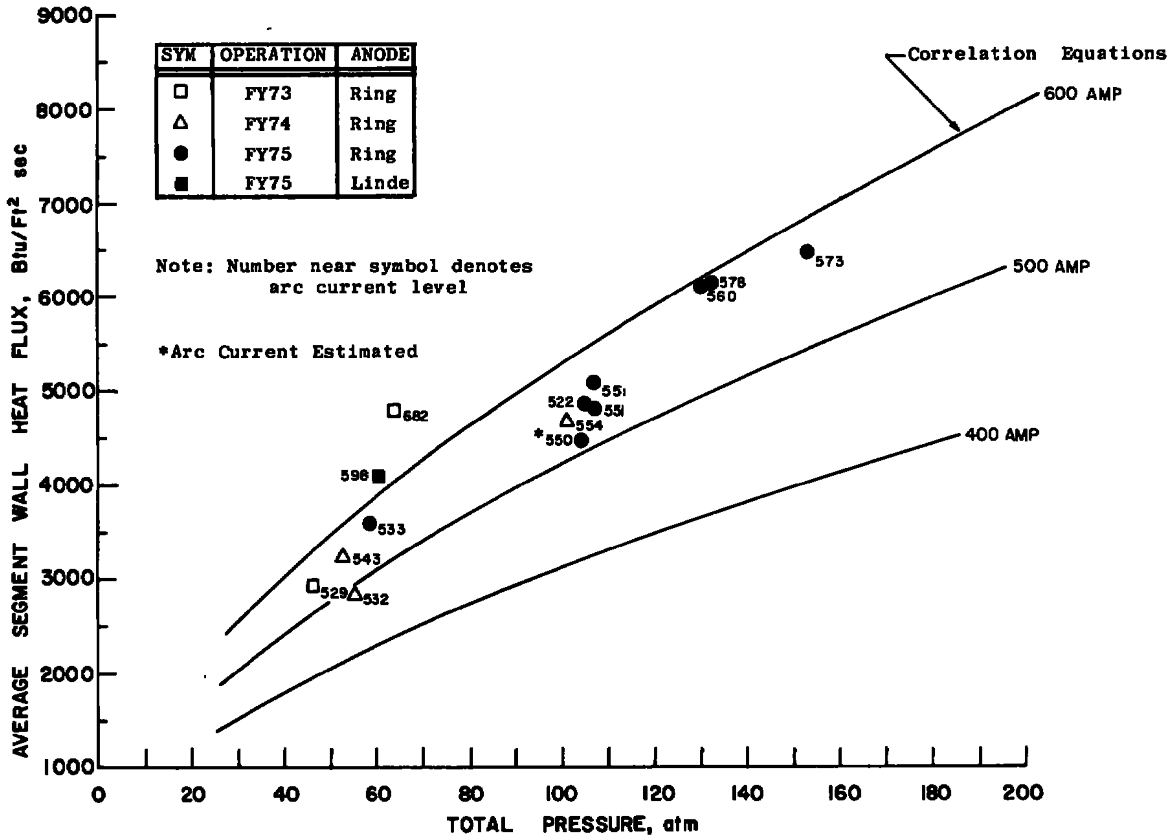


Figure 11. Average channel wall heat flux.

To properly design a channel segment configuration, a realistic knowledge of the voltage gradient that must be sustained at the channel wall is essential. Measured and calculated values of the voltage gradient encountered for the 5-MW segmented arc are shown in Fig. 12. The maximum measured gradient was 372 v/in. at 171-atm chamber pressure. Correlation values were based on Eq. (1). The voltage gradient was primarily a function of total pressure and only slightly affected by arc current.

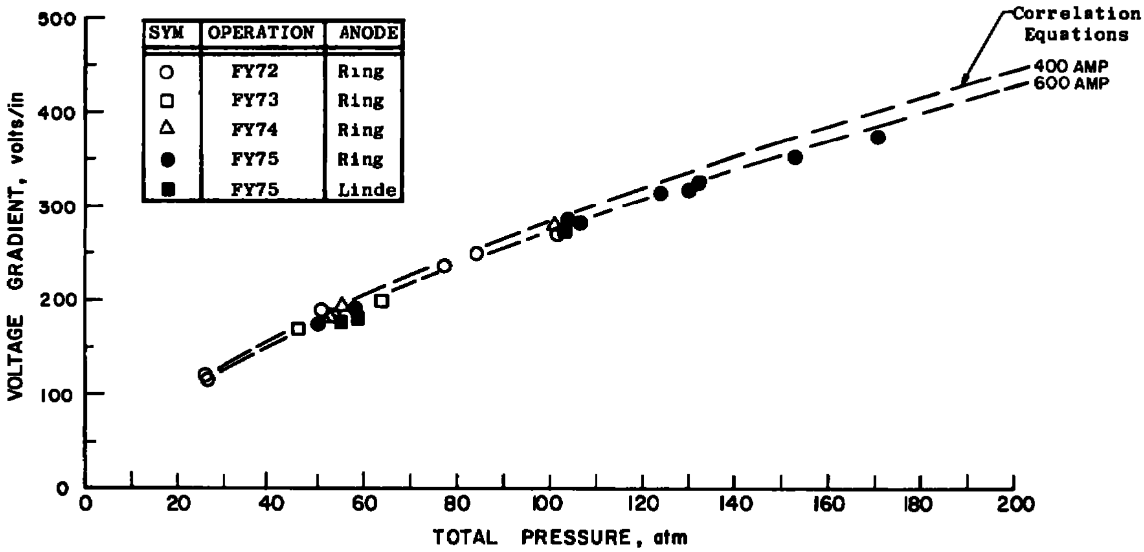


Figure 12. Measured and predicted voltage gradient.

3.2.3 Endurance Run

As stated in Section 3.1, an extended run of 60 sec was made to evaluate the feasibility and temporal stability of longer runs. Figure 13 shows a record of measured values of arc voltage, chamber pressure, and bulk enthalpy plotted every 10 sec and at smaller intervals during the first 10 sec of operation. Voltage and current were within ±2 percent of their final values after 2 sec from arc initiation, and enthalpy after 8 sec of operation. The heater operation was extremely steady, and no variation occurred in the level measured of any parameter after 10 sec of operation.

3.3 MODEL DATA

Impact pressure profiles of the nozzle exit flow are shown in Fig. 14 for chamber pressures of 107, 132, and 153 atm. A pressure probe containing a high response transducer was used to measure these stagnation point pressures. The profiles continue to be "flat" for chamber pressures above 100 atm, similar to the profiles for pressures below 100 atm reported in Ref. 4.

Total enthalpy profiles of the exit flow are presented in Fig. 15 for the 153-atm operation (Run 6). The inferred enthalpy profile was calculated utilizing the laminar Fay-Riddell theory, the pressure profile data (Fig. 14), and heat-transfer measurements made with a null-point calorimeter probe. The measured enthalpy profile was obtained from

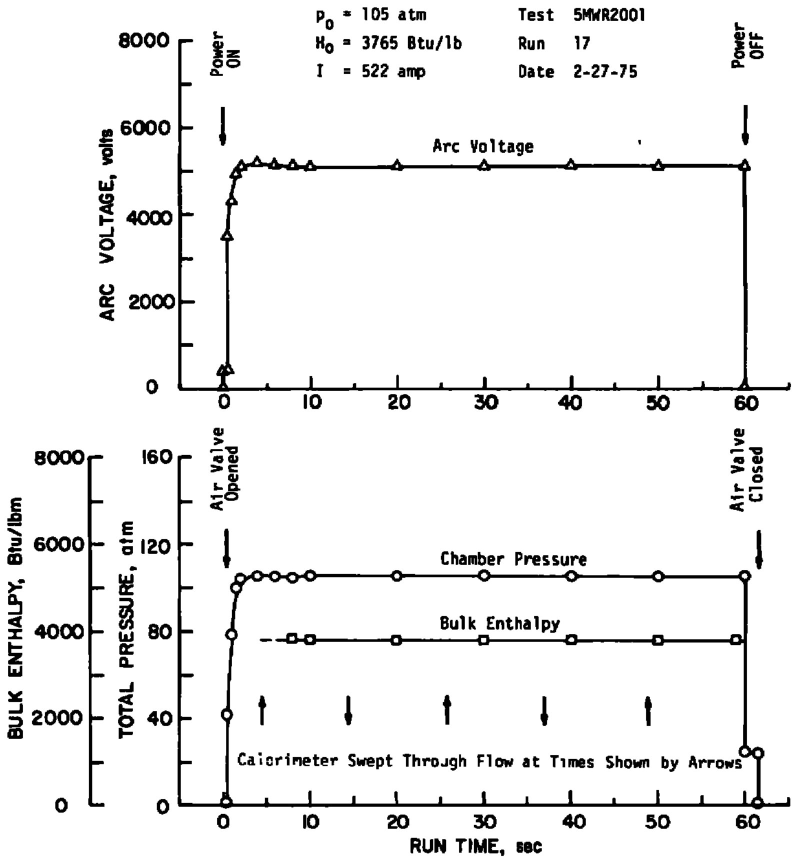


Figure 13. Endurance run.

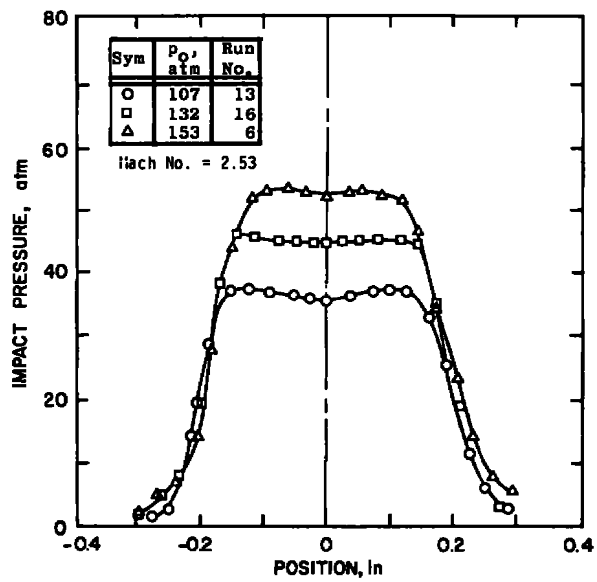


Figure 14. Impact pressure profiles at nozzle exit.

enthalpy probe data (Ref. 5). The average centerline inferred enthalpy was about 6,700 Btu/lb compared to a measured enthalpy of 3,360 Btu/lb and a bulk enthalpy of 3,500 Btu/lb. The inferred enthalpy data may be influenced by free-stream turbulence effects on the heat transfer. While the shape of the profiles in Fig. 15 are not identical, neither show any evidence of centerline "peaking." The same conclusion was reached for pressures below 100 atm (see Ref. 4).

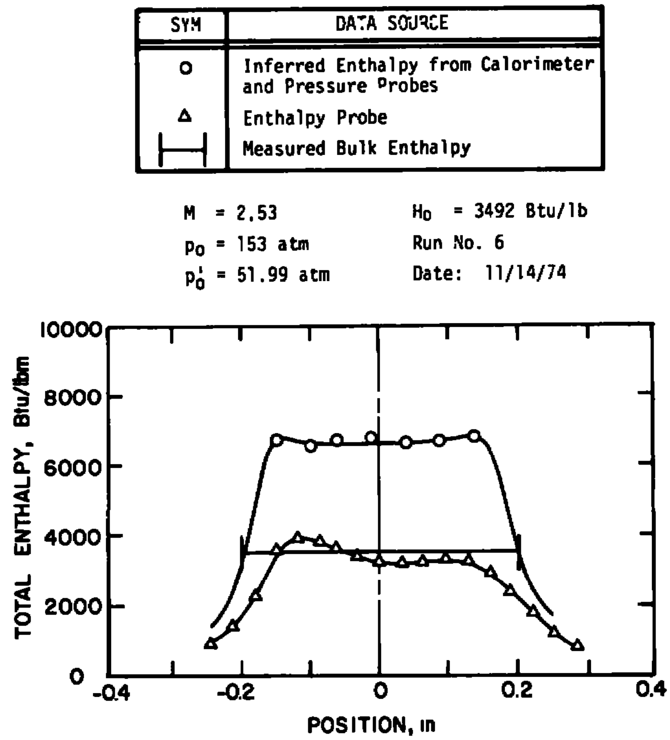


Figure 15. Total enthalpy profiles at nozzle exit.

Heat-transfer profiles are shown in Fig. 16 for five consecutive sweeps of a null-point calorimeter during the 60-sec endurance test (Run 17). Sweep direction and time of injection are shown in Fig. 13. Centerline values ranged from 9,600 Btu/ft^2-sec for the first sweep to 10,800 Btu/ft^2-sec for the final sweep, representing a variation of ±6 percent. Again, centerline "peaking" was not observed on any of these traverses; however, high heat-transfer rates did occur near position 0.15 in., especially on sweep 5. The reason for the nonsymmetric profile was undetermined and was not typical on other runs.

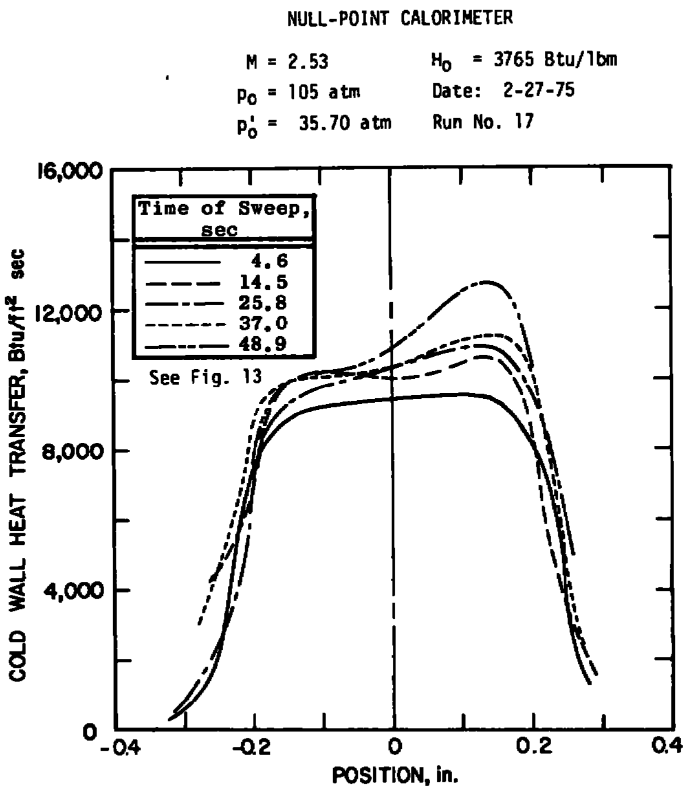


Figure 16. Nozzle exit heat-transfer profiles for the endurance run.

3.4 COMPARISON OF PERFORMANCE WITH OTHER ARC HEATERS

The performance of the AEDC 5-MW segmented heater is compared with other existing arc heaters in Fig. 7. Operation of the AEDC 5-MW segmented arc between 30 and 150 atm has produced enthalpies 60- to 70-percent higher than the best performance generally reported for other high-pressure arc heaters. Other existing segmented arc heaters have also produced high enthalpies, but they have not been operated above 30-atm pressure and generally operated below 15 atm. Thus, the AEDC 5-MW segmented arc heater has a unique performance capability of high enthalpy at high pressure. If minor modifications are made to allow higher arc currents, even higher performance can be expected.

4.0 CONCLUDING REMARKS

During the series of tests described in this report, the AEDC 5-MW segmented arc heater was operated at pressures up to five times higher than reported for other heaters of this type. No inherent difficulties were encountered which would prevent operation at pressures greater than 150 atm. Segment failures resulted almost entirely from wall deformation and not overheating. Average wall heat fluxes up to nearly 6,500 Btu/ft^2-sec were measured without segment failure. Bulk enthalpy levels were up to 70-percent higher than reported for other existing high-pressure arc heaters. A correlation program was used which accurately predicts the heater performance. Nozzle exit profiles of impact pressure and total enthalpy were basically flat with no centerline peaking. The effluent was observed to be clean and to have relatively steady intensity. Experience was gained in the operation of the segmented arc at pressures up to 171 atm, and several hardware configurations were evaluated and optimized. These data have been of great value during the design of the large segmented heater.

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Table 1. 5-MW Segmented Arc Data Summary

Throat Diam - 0.215 in.

FY75

Test 5MWR2001			Arc Heater Data						Model Data on Centerline of Flow				Remarks
									Enthalpy Probe	Null-Point Calorimeter		Impact Pressure Probe	
Run	Date	Run Time, sec	p_o, atm	I, amp	V, volts	$\dot{m}$, lb/sec	H_o, Btu/lb	η, %	H_p	$\dot{q}_{cw}$	H_{inf}	p_o'	
1	10-10-74	4.1	50.5	556	3140	0.126	-	-	Model Injection System			NA	Arc attachment on both electrodes upstream of optimum
2	10-23-74	16.1	58.5	533	3420	0.138	4634	36.3	Model Injection System			NA	Arc attachment optimized at both anode and cathode
3	10-25-74	15.1	107	551	5050	0.266	4101	40.3	Model Injection System			NA	Arc attachment upstream of optimum on both electrodes
4	11-06-74	5.2	124	573	5620	0.325	3934*	40.8*	-	-	-	42.8	Three models injected; recorder on low speed
5	11-12-74	12.0	130	560	5670	0.343	3612	40.7	-	11,400	6,200	43.0	Enthalpy probe damaged prior to run
6	11-14-74	12.1	153	573	6320	0.424	3492	41.8	3,360	13,600	6,700	53.0	Arc attachment nearly optimum on both electrodes
7	11-18-74	3.1	171	575	6700	0.460	3373*	41.2*	Models Not Injected.				Channel segment failed at 2.8 sec
8	12-16-74	5.1	LINDE ANODE MODIFICATION, TIE-BOLT INSULATOR BREAKDOWN: EXTERNAL ARC										
9	12-20-74	5.0	55.2	515	4140	0.128	5706*	35.6*	Models Not Injected				Arc attachment normal on both electrodes.
10-1	12-30-74	15.0	59.0	590	4280	0.135	5591	30.9	NA	11,600	9,000	20.4	Normal arc length
10-2			60.5	598	4080	0.135	5690	32.5	-	-	-	-	Short arc; arc attachment on anode at down-stream end; segment failed at end of run.
11	1-03-75	4.6	102.0	555	6480	0.262	4477*	33.7*	Models Not Injected.				Three channel segments destroyed.
12	1-15-75	1.1	84.1	591	4256	0.259	-	-	ORIGINAL ANODE CONFIGURATION				Heater cut off before conditions stabilized
13	1-23-75	7.9	107	551	5050	0.279	4005	41.3	NA	9,000	5,300	35.5	No problems encountered.
14	2-10-75	8.0	104	550*	5090	0.264	4357*	42.4*	Models Not Injected				Three 20-MW prototype segments installed.
15	2-14-75	2.8	130	-	5770	0.343	-	-	Models Not Injected.				Channel segment failed.
16	2-21-75	10.0	132	578	5800	0.343	3814	40.6	NA	9,500	5,100	44.8	Two 20-MW prototype segments survived undamaged.
17	2-27-75	60.1	105	522	5120	0.278	3765	40.2	NA	10,200	6,000	-	Moderate anode erosion.

*Estimated NA - Not available.

Table 2. Descriptive Test Summary for FY75

TEST 5MWR2001

Run	Objective	Configuration	Remarks
1	Short shakedown run at 50 atm, 550 amp	Initial configuration shown in Fig. 3, except four upstream segments were installed. Ten welded segments and 37 silver-soldered segments (of which 21 were new) were installed in the channel. The 0.067-in.-diam orifice was installed in the air line to the end plate; the 0.018-in.-diam orifice was in the air line to the downstream air injection ring. A new tubular cathode assembly and a modified end plate allowed inspection of the heater at each end.	The run was good and no damage occurred to any components. The heater was inspected from both ends after the run without removing it from the stand. The arc attachment location on both electrodes was upstream of optimum, indicating a need for redistribution of the air supply.
2.	Energy balance run at 55 atm, 525 amp	Same as Run 1, except 0.0785-in.-diam orifice installed in air line to end plate and 0.028-in.-diam orifice installed in the air line to downstream air injection ring.	Run was excellent and arc attachment locations were nearly optimized at both the anode and cathode.

Table 2. Continued

Run	Objective	Configuration	Remarks
3	Energy balance run at 100 atm, 540 amp	Same as Run 2, except the 0.089-in.-diam orifice installed in air line to the end plate.	Run was good and no damage was encountered. Arc attachment slightly upstream of optimum on both anode and cathode. Two welded segments had "hot spots" on them after the run; X-rays revealed partial blockage of water passage on both segments. Anode liner was severely eroded and ready for replacement (this liner was used continuously since Run 18 in FY72 with an accumulated time of 200 sec)
4	Short run at 125 atm, 550 amp	Same as Runs 2 and 3, except the 0.1015-in.-diam orifice installed in air line to the end plate. Changed anode liner (used).	Check run was good. Arc attachment was slightly downstream of optimum on anode and slightly upstream of optimum on the cathode. Boron nitride insulator adjacent to upstream air injection ring eroded severely by the cold air swirl.
5	Energy balance run at 125 atm, 550 amp	Same as Run 4, except the 0.037-in.-diam orifice installed in the air line to the downstream air injection ring. Installed Mykroy insulator adjacent to upstream air ring.	Heater was in good condition after the run. Arc attachment optimized on anode, slightly upstream of optimum on the cathode. Mykroy insulator adjacent to upstream air ring was not eroded by air swirl.
6	Energy balance run at 150 atm, 550 amp	Same as Runs 4 and 5, except the 0.0465-in.-diam orifice installed in the air line to downstream air injection ring.	No problems were encountered during the run, and post inspection showed the heater to be in excellent condition. Arc attachment was nearly optimum on both electrodes.

Table 2. Continued

Run	Objective	Configuration	Remarks
7	Energy balance run at 165 atm, 560 amp	Same as Run 6	A channel segment burned through after 2.8-sec run time. The heater was fully pressurized; however, some fluctuations in voltage and chamber pressure were observed prior to the segment failure. Peak chamber pressure pulse was 186 atm. The wall was deformed on the inside surface of six silver-soldered channel segments, probably caused by the high gas pressure and wide segment wall. The electrodes and other areas of the heater were undamaged.
8	Shakedown run with Linde-type anode at 55 atm, 530 amp	Linde-type anode and adaptor pieces installed upstream of channel segments as shown in Fig. 5. The 0.037-in.-diam orifice installed in the air line to the downstream air injection ring.	Vacuum start was normal, however, external arc occurred as airflow was initiated. Power was terminated 5.1 sec after arc initiation. Damage was minor and was confined primarily to external tubes and insulators. External arc caused by insufficient insulation on tie bolts.
9	Same as Run 8	Same as Run 8; external insulation on tie bolts and cathode water manifold improved.	Check run was good; the chamber pressure and voltage were free of fluctuations. Arc attachment locations optimum on both electrodes.

Table 2. Continued

Run	Objective	Configuration	Remarks
10	Energy balance run at 60 atm, 550 amp	Same as Run 9	The heater run was normal for 6.6 sec, then the arc length shortened to near the downstream end of the anode tube. Attachment also occurred on the channel transition piece upstream of the channel. No damage occurred and the heater performance was not altered significantly (compare data summary points 10-1 and 10-2). Channel segment failed 0.1 sec prior to normal shutdown, but did not affect the run.
11	Energy balance run at 100 atm, 550 amp	Same as Runs 9 and 10	The heater run was normal for 3.6 sec, then arc attachment apparently occurred along channel wall at 15 to 20 segment positions in the downstream half of the channel. Three segments failed at 4.3 sec, which resulted in heater cutoff at 4.6 sec. Arc attachment at the anode looked normal after the run. Damage was confined to the three segments that failed and some minor external hose and insulator damage.
12	Energy balance run at 105 atm, 550 amp	Linde-type anode was replaced with the original ring-type electrode. Configuration same as Run 5, except the 0.089-in.-diam orifice was installed in the air line to the end plate.	Vacuum check indicated small water leak prior to run; therefore, pressure in the heater was above normal. After open circuit voltage was applied momentarily, the heater start was normal. After 1.1 sec the run was inadvertently terminated. No damage occurred to the heater. The water leak was from a silver-solder joint in a tapered segment. About 80 percent of the intended chamber pressure was reached before the run was terminated.

Table 2. Continued

Run	Objective	Configuration	Remarks
13	Same as Run 12	Same as Run 12	Run was good and no damage occurred to any heater components. Arc attachment was slightly upstream of optimum on the anode ring. Cathode attachment was normal.
14	Energy balance run at 105 atm, 550 amp to evaluate three 20-MW prototype segments	Same as Runs 12 and 13 except three 20-MW prototype segments were installed (one straight and two tapered segments were installed at the downstream end of the channel).	General condition of the heater was good after the run. Arc attachment was normal on both electrodes. Minor erosion occurred on one 20-MW prototype segment indicating possible arc attachment, but in general the three prototype segments were undamaged.
15	Energy balance run at 130 atm, 560 amp	Same as Run 14, except the 0.1015-in.-diam orifice was installed in the air line to the end plate and the 0.0465-in.-diam orifice was installed in the line to the downstream air ring.	Vacuum check revealed water leak prior to run; the heater run was normal for 2.4 sec and chamber was fully pressurized, then a channel segment failed and terminated the run. The wall of two 20-MW prototype segments collapsed and an internal water leak was found in the third one, which apparently caused the water leak before the run.
16	Same as Run 15	Same as Run 15, except the three original 20-MW prototype segments were removed. Two replacement prototype segments were installed at the tapered locations.	Run was good and no damage occurred to any heater components. Arc attachment nearly optimized on both electrodes. The two 20-MW prototype segments were not damaged.

Table 2. Concluded

Run	Objective	Configuration	Remarks
17	60-sec endurance run at 100 atm, 520 amp	Same as Run 16, except the 0.037-in.-diam orifice installed in air line to the downstream air injection ring.	Heater ran successfully for 60.1 sec without problems. Arc attachment was optimized on both electrodes; no evidence of any damage inside the heater. The anode surface was moderately eroded but had been installed since Run 12.

NOMENCLATURE

D^*	Nozzle throat diameter, in.
H_{inf}	Total enthalpy inferred from heat-transfer rate, Btu/lbm
H_o	Total enthalpy from energy balance, Btu/lbm
H_p	Total enthalpy from enthalpy probe, Btu/lbm
H_s	Sonic flow enthalpy, Btu/lbm
I	Arc current, amp
M	Mach number
$\dot{m}$	Air mass flow rate, lbm/sec
p_o	Total pressure, atm
p_o'	Impact pressure, atm
$\dot{q}_{cw}$	Cold wall heat flux, Btu/ft^2-sec
V	Arc voltage, v
η	Efficiency, percent

SUBSCRIPTS

corr	Correlation value